

## Heat and Gas Transport Characteristics in Differently-Decomposed Peaty Soils at Variably-Saturated Conditions

S. H. Dissanayaka<sup>1</sup>, S. Hamamoto<sup>1,2</sup>, K. Kawamoto<sup>1,2</sup>, T. Komatsu<sup>1,2</sup>

<sup>1</sup>Department of Civil and Environmental Engineering  
Saitama University  
JAPAN

<sup>2</sup>Institute for Environmental Science and Technology  
Saitama University  
JAPAN

E-mail: [himalika.shire@gmail.com](mailto:himalika.shire@gmail.com)

**Abstract:** Knowledge of heat and gas transport properties of the peat soils is important to simulate greenhouse gas behaviour and changes of soil-temperature in the wetlands. In this study, the heat and gas transport properties for differently-decomposed and variably saturated peat soils were measured in order to investigate the general analogies and differences between transport properties of the peat soils. As results, changes in liquid-phase tortuosity under different moisture conditions and volume shrinkage under dry conditions did not significantly affect the thermal conductivity, showing linear increase of thermal conductivity with moisture content. On the other hand, marked effects of soil-water blockage and volume shrinkage on the soil-gas diffusion coefficient under wet and dry conditions, respectively, were observed.

**Keywords:** Wetland, Peat soil, green house gas, gas transport, heat transport.

### 1. INTRODUCTION

Humus-rich peaty soils in wetlands are known as one of the major sources of global carbon which emits the greenhouse gases to the atmosphere (e.g., Alm et al., 1999; Pilegaard et al., 2003). Knowledge of gas transport characteristics in differently-decomposed and variably textured peaty soils is important for simulating the emissions of the greenhouse gases, especially methane, from the wetlands (e.g., Alm et al., 1999; Pilegaard et al., 2003). In addition, since soil temperature in the wetlands is a key factor to control the microbiological and chemical processes, better understandings of heat transport characteristics in the peaty soils are required for accurate simulations of greenhouse gas production and emissions. Unique physical characteristics of peaty soils such as high organic matter content, high total porosity and volume shrinkage may influence various transport properties of peaty soils. Objectives of this study are to measure the heat and gas transport properties for peat soils at variably saturated conditions and discuss the possible analogies and differences between various transport properties of peat soils.

### 2. MATERIALS AND METHODOLOGY

Soil samples for this study was obtained from the Hokkaido Bibai marsh, Japan (43°19' N, 141°48' E). Undisturbed peat samples were taken from three different sites in Bibai marsh at different depths using 100cm<sup>3</sup> cylindrical cores (i.d. 5.01cm, length 5.11cm). Peat 1 samples were sampled inside the marsh area, while Peat 2 samples were sampled from the area nearby a drainage ditch surrounding the marsh. Peat 3 samples were obtained from forested area located outside the wetland. Basic soil physical and chemical properties are tabulated in Table 1.

**Table 1 Physical and chemical properties for soil samples.**

	Depth	Layer	Water Content	Particle density	Dry bulk density		Porosity				
					Saturated	Air dried	cm <sup>3</sup> cm <sup>-3</sup>	LOI %	SOC %	C/N	pH <sup>†</sup>
	cm		%	g cm <sup>-3</sup>	g cm <sup>-3</sup>	g cm <sup>-3</sup>					
Peat 1	0	H1	942	1.42	0.07	0.09	0.96	97.00	44.60	48.00	5.8
	5	H2	1233	1.44	0.05	0.12	0.94	91.10	65.70	67.00	5.6
	10	H2	1211	1.42	0.07	0.08	0.93	89.34	60.60	28.00	3.1
	15	H3	854	1.65	0.10	0.16	0.92	74.50	29.60	17.00	4.6
	20	H3	573	1.49	0.16	0.26	0.86	36.17	33.30	19.00	5.1
	30	H3	591	1.37	0.16	0.23	0.92	47.54	36.50	26.00	4.8
Peat 2	0	AH	124	2.05	0.31	0.39	0.85	55.94	66.09	33.17	4.3
	10	AH	282	2.63	0.17	0.24	0.94	46.55	89.70	41.75	4.5
	20	H1	699	1.86	0.09	0.17	0.95	95.25	72.89	54.46	4.6
	30	H2	959	1.70	0.09	0.12	0.95	95.70	86.70	84.74	3.5
	40	H2	922	1.44	0.08	0.10	0.91	94.37	86.63	81.28	4.6
	50	H2	954	1.80	0.09	0.16	0.94	94.61	72.82	85.02	4.3
	60	H2	762	1.51	0.10	0.16	0.91	97.72	71.28	90.77	4.8
Peat 3	0	H1	81	1.93	0.24	0.36	0.92	48.00	31.27	28.59	4.3
	10	H2	315	1.58	0.14	0.34	0.92	32.80	52.62	27.00	4.1
	20	H2	488	1.49	0.10	0.19	0.90	94.70	50.87	25.67	4.1
	30	H2	720	1.54	0.09	0.19	0.92	91.23	64.78	28.79	4.6
	40	H2	833	1.52	0.09	0.20	0.94	93.33	81.24	23.83	5
	60	H3	953	1.48	0.08	0.15	0.93	84.53	81.64	28.55	4.8
	90	C1	419	2.08	0.27	0.38	0.90	52.10	43.37	24.91	4.6
	100	C1	277	2.04	0.45	0.62	0.91	24.80	27.26	25.21	4.5
	120	C1	196	2.32	0.19	0.28	0.95	27.00	28.33	24.40	4.6
	150	C2	71	2.64	0.75	1.62	0.71	8.40	3.23	16.26	5.1

<sup>†</sup> pH was measured directly by using extracted soil solution.

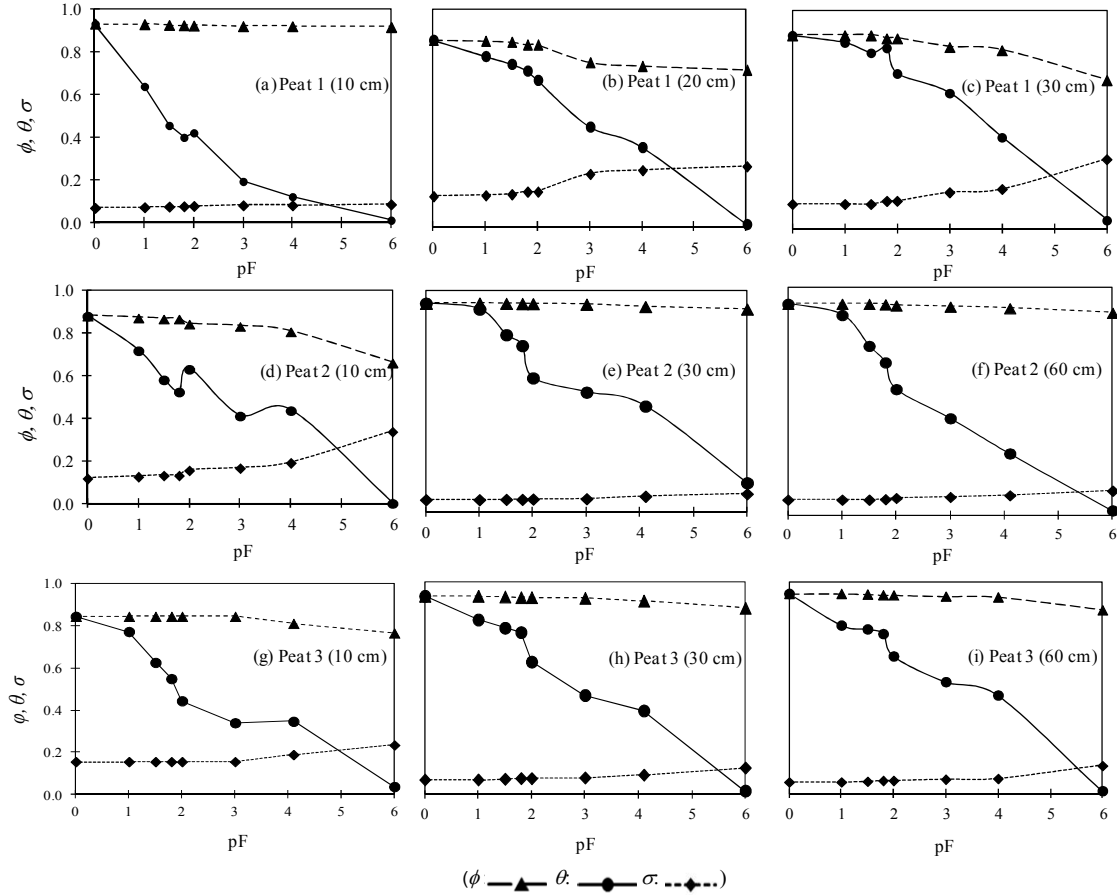
The peat samples were initially saturated and subsequently drained using two different methods corresponding to the matric suction ranges. A hanging water suction method was used for low matric suctions up to pF 2 (- 100 cm H<sub>2</sub>O) and a pressure plate apparatus for medium suctions (pF 2 to pF 4, i.e., - 100 cm H<sub>2</sub>O to -10000 cm H<sub>2</sub>O). The sample cores were then oven-dried at 30°C for three days and kept in a climate controlled room at 25°C and a relative humidity of 60% for three days to reach air-dry condition (Resurreccion et al., 2008). The thermal conductivity ( $\lambda$ ) and gas diffusion coefficient ( $D_p$ ) were measured at different soil moisture suction levels. The thermal conductivity of the samples was measured by using Decagon KD2-Pro probe. The gas diffusion coefficient was measured using a chamber method where oxygen was used as a tracer gas.

### 3. RESULTS AND DISCUSSION

#### 3.1. Water retention characteristics and volume shrinkage during drying

Figure 1 shows the changes in the total porosity ( $\Phi$ ), volumetric water content ( $\theta$ ), and volumetric solids content ( $\sigma$ ) for Peat 1-3 samples as a function of pF at different depths. All soils except the surface layers (i.e., to 10 cm depth), exhibited high water retention characteristics up to pF 1.8 where around 60-80% of water saturation was still retained. This characteristic clearly indicates a formation of a well-developed organic matrix with micro-pore structure that increased with increasing degree of

decomposition. Most peat soil samples showed a decrease of  $\phi$  and increase of  $\sigma$  with increasing pF after around pF 1.8 due to volume shrinkage of the samples during drying. Most of the samples showed peaks in  $\theta$  at around pF 2 indicating a reduction in total soil volume (and thus increase in  $\sigma$ ) caused a relative increase in  $\theta$ , although soil-water for each sample drained with increasing pF at the range of pF 1.5-2.0.



**Figure 1** Total porosity ( $\phi$ ), volumetric water content ( $\theta$ ), and volumetric solid content ( $\sigma$ ) for Peat1, Peat 2, and Peat 3 samples as a function of pF (=  $\log |\psi|$ , where  $\psi$  is in cm H<sub>2</sub>O).

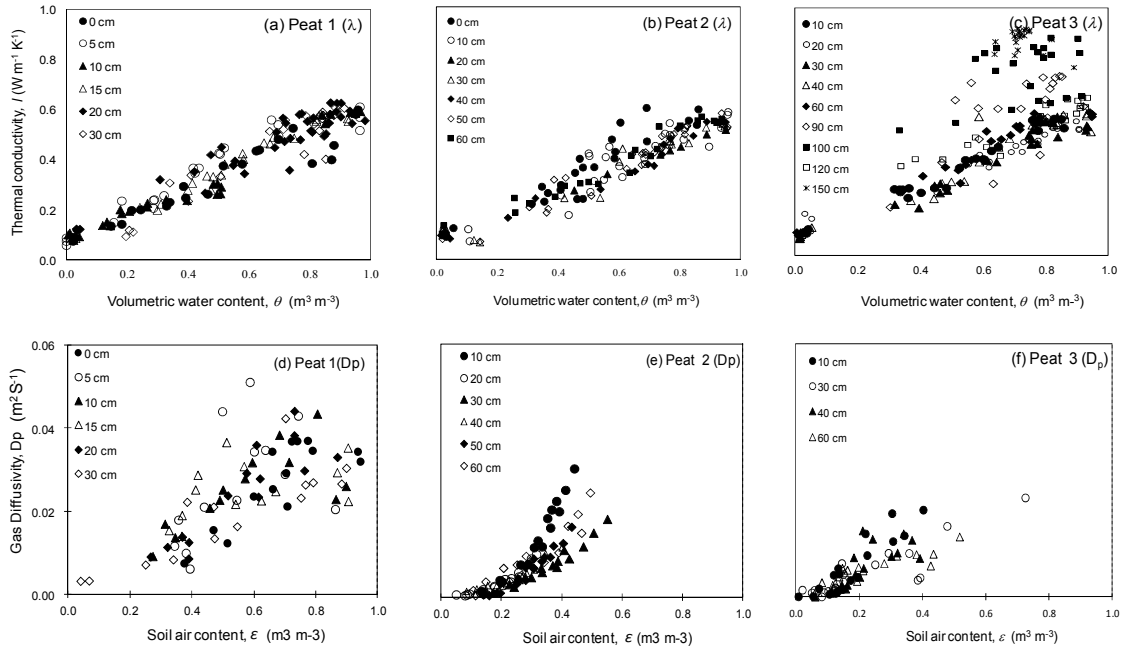
### 3.2. Measured thermal conductivity and gas diffusion coefficient of peat soil under variable-Saturated conditions

Figure 2 shows the measured thermal conductivities ( $\lambda$ ) and gas diffusion coefficients ( $D_p$ ) for three different peat soil samples as a function of volumetric water content ( $\theta$ ) and soil air content ( $\varepsilon$ ), respectively. Both transport properties,  $\lambda$  and  $D_p$  showed increase with increasing fluid content (i.e., soil water content or soil air content, m<sup>3</sup> m<sup>-3</sup>).

Thermal conductivity ( $\lambda$ ) of the mineral soils is rapidly increasing with increasing  $\theta$  especially at dry conditions due to the improvement of thermal contacts between soil particles by soil water (Becker et al., 1992; Hamamoto et al., 2010). A linear increase of  $\lambda$  with increasing  $\theta$  was observed in all three peat soils. This suggests that water content and liquid-phase tortuosity are the most controlling factors for the  $\lambda$ , as supported by the fact that the thermal conductivity of organic matter (0.25 W m<sup>-1</sup> K<sup>-1</sup>) is much

lower than that of water ( $0.57 \text{ W m}^{-1} \text{ K}^{-1}$ ) (de Vries, 1963; Brovka & Rovdan, 1999). The Thermal conductivity for Peat 3 at deeper layers showed higher values than those for other peat types. Difference in mineral composition in the deeper layers might affect this characteristic behaviour as partially expected by lower loss on ignition (LOI) values and higher particle density ( $\rho_s$ ) values of the soil samples.

The  $D_p$  rapidly increased at high  $\varepsilon$ , indicating gas transport in soils is highly enhanced through well-connected, large-pore networks under dry conditions (Hamamoto *et al.*, 2010). In addition, the  $D_p$  data clearly suggests the existence of percolation thresholds which is inactive air-filled pore space due to soil-water blockage.



**Figure 2 Thermal conductivities ( $\lambda$ ) and gas diffusivities ( $D_p$ ) as functions of volumetric water content ( $\theta$ ) and soil air content ( $\varepsilon$ ) for Peat 1, Peat 2 and Peat 3 samples.**

### 3.3. Application of Archie's Second Law with Reference Point to Thermal Conductivity and Gas Diffusivity

Under fluid-unsaturated conditions, a generalized Archie's second law (Archie, 1942) for transport parameters with reference point can be written as,

$$\frac{P}{P_{ref}} = \left( \frac{\phi}{\phi_{ref}} \right)^n \quad (1)$$

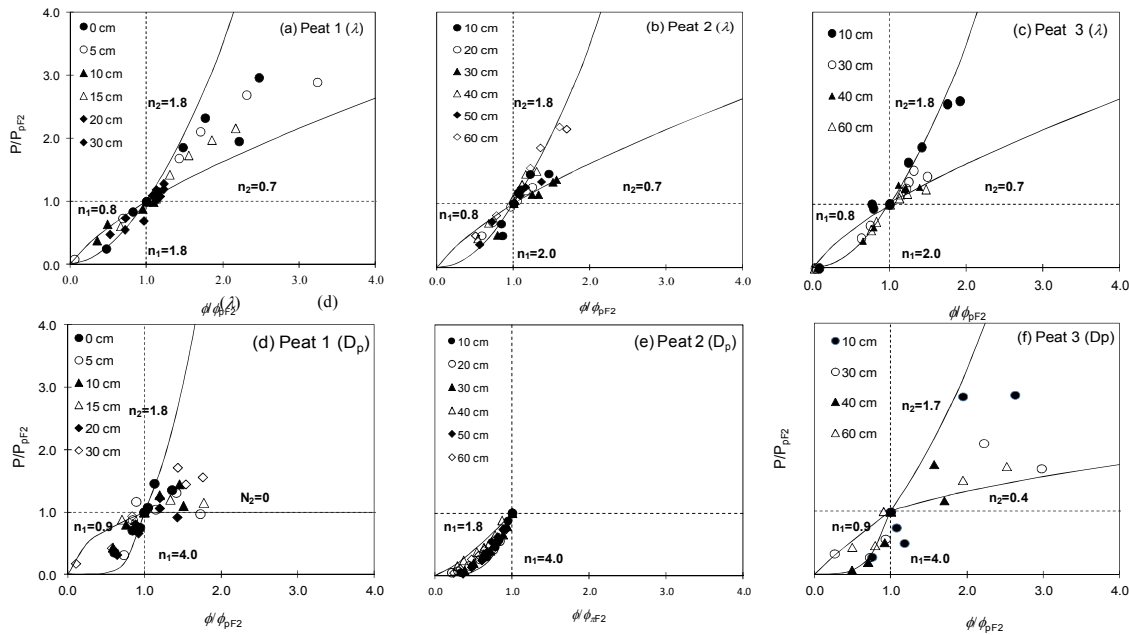
where  $P$  is the bulk parameter value under fluid-unsaturated conditions (i.e.,  $\lambda$  and  $D_p$ ),  $P_{ref}$  is the bulk parameter value at the reference point,  $\phi$  is the fluid content (i.e., soil water content for  $\lambda$  and soil air content for  $D_p$ ,  $\text{m}^3 \text{ m}^{-3}$ ),  $\phi_{ref}$  is the fluid content at the particular reference point and  $n$  is the saturation exponent representing a fluid-pore tortuosity-connectivity in porous media.

In this study, the pF 2 was selected as a reference point since the peat soils at less than pF 2 (wet condition) do not exhibit significant volume shrinkage as shown in Figure 1. Therefore, dry (region 1) and

wet (region 2) regions for  $\lambda$ , and wet (region 1) and dry (region 2) regions for  $D_p$  were defined for matric potential regions  $\leq pF 2$  and  $> pF 2$ , respectively. In addition,  $\lambda$  at dry condition ( $\lambda_{dry}$ ) was considered in both  $P$  and  $P_{ref}$ , giving  $P/P_{ref}$  of  $(\lambda - \lambda_{dry})/(\lambda_{pF2} - \lambda_{dry})$  where  $\lambda_{pF2}$  is the  $\lambda$  value at  $pF 2$ . The  $n$  values for each region 1 and 2 were defined as  $n_1$  and  $n_2$ , respectively.

Figure 3 shows the normalized parameter values,  $P/P_{ref}$ , for each parameter as a function of normalized fluid content,  $\phi/\phi_{ref}$ , ( $\theta/\theta_{pF2}$  for  $\lambda$  and  $\varepsilon/\varepsilon_{pF2}$  for  $D_p$ , where  $\theta_{pF2}$  and  $\varepsilon_{pF2}$  are  $\theta$  and  $\varepsilon$  at  $pF 2$ , respectively). Table 2 shows the best fit  $n_1$  and  $n_2$  values for thermal conductivity and gas diffusivity of each peat soils at different depth.

The normalized  $\lambda$  values generally showed a linear trend as a function of fluid content, giving  $n_1$  is ranging from 0.8 to 2.0 and  $n_2$  is ranging 0.7 and 1.8. Again, this supports that  $\lambda$  is mainly governed by a degree of water saturation and soil-moisture dependency on liquid-phase tortuosity for thermal conductivity is small. In addition, almost similar  $n_1$  and  $n_2$  values (average value of 1.0) for each peat soil at different depths (Table 2) suggest less effects of volume shrinkage on the  $\lambda$ .



**Figure 3 Normalized parameter value,  $P/P_{pF2}$ , as a function of normalized fluid content,  $\phi/\phi_{pF2}$ , for Peat 1, Peat 2 and Peat 3 samples.**

For  $D_p$ , the normalized  $D_p$  values showed a two-region behaviour against fluid content. Higher  $n_1$  values ranging 0.9 to 4.0 as compared to those for the  $\lambda$  indicate the significant effects of soil-water blockage on gas diffusion process under dry conditions. The  $n_2$  values for the  $D_p$  were generally lower than those for  $\lambda$  and more wider range of  $n_2$  values were obtained (Fig. 3 and Table 2). The findings suggest that increase in air-phase tortuosity dramatically reduced incremental increase in the  $D_p$  under dry conditions.

**Table 2 Best fit  $n_1$  and  $n_2$  values for thermal conductivity and gas diffusivity of each peat soils at different depth**

soil		$n_1$		$n_2$	
		$\lambda$	$D_p$	$\lambda$	$D_p$
Peat 1	0 cm	1.5	3.0	1.2	1.5
	5 cm	0.8	2.0	1.1	0.3
	10 cm	0.8	1.5	1.0	0.5
	15 cm	1.5	-	1.1	0.3
	20 cm	1.3	3.0	0.9	0.0
	30 cm	2.1	1.5	1.0	1.0
Peat 2	10 cm	2.0	2.9	1.2	-
	20 cm	1.2	2.6	1.1	-
	30 cm	-	2.6	0.7	-
	40 cm	1.1	1.5	2.2	-
	50 cm	1.4	2.4	1.2	-
	60 cm	0.9	2.2	1.7	-
Peat 3	10 cm	-	-	1.6	1.3
	30 cm	1.5	4.5	1.0	0.9
	40 cm	2.0	5.0	1.0	0.7
	60 cm	1.9	2.0	0.7	0.6

#### 4. CONCLUSIONS

In this study, thermal conductivity ( $\lambda$ ) and diffusion coefficient ( $D_p$ ) for differently-composed peat soils at variably-saturated conditions were measured, and heat and gas transport characteristics were characterized by applying Archie's second law with a reference point of  $pF$  2 to the measured data.

Linear increase in normalized  $\lambda$  values as a function of fluid content for all peaty soils except for soils with high mineral contents suggested that changes in liquid-phase tortuosity under different moisture conditions and volume shrinkage under dry conditions do not significantly affect the  $\lambda$  behavior. On the other hand, normalized  $D_p$  values suggested marked effects of soil-water blockage and volume shrinkage on the  $D_p$  under wet and dry conditions, respectively.

The fitted  $n$  values by the Archie's law for the  $\lambda$  were ranged from 0.8 to 2.0 (on average 1.0) for dry and wet regions. In general, as compared to  $\lambda$ , higher and lower  $n$  values for the  $D_p$  under wet and dry regions were obtained, respectively. In perspective, the obtained differences in the  $n$  values of the  $\lambda$  and  $D_p$  will be associated with physical and chemical properties such as organic matter content or clay content and unified predictive models of  $\lambda$  and  $D_p$  considering key factors to control  $\lambda$  and  $D_p$  behaviors will be proposed.

#### 5. ACKNOWLEDGEMENT

This study was made possible by the Japan Science and Technology Agency (JST) CREST project, and JSPS bilateral research projects, JSPS Asia and Africa Science Platform Program, and JST- the Japan International Cooperation Agency (JICA) Science and Technology Research Partnership for Sustainable Development (SATREPS) project.

## 6. REFERENCES

- Alm, J., Saarnio, S., Nykanen, H., Silvola, J. and Martikainen, P. J. (1999), *Winter CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes on some natural and drained boreal peatlands*, Biogeochemistry 44, pp. 163-186.
- Archie, G.E. (1942). *The electrical resistivity log as an aid in determining some reservoir characteristics*, Transactions of the American Institute of Mining, Metallurgical and Petroleum Engineers, 146, pp. 54–62.
- Becker, B. R., Misra, A. and Fricke, B. A. (1992), *Development correlations for soil thermal conductivity*, International Communications in Heat and Mass Transfer, 19, pp. 59-68.
- Brovka, G. P. and Rovdan, E. N. (1999), *Thermal conductivity of peat soils*, Eurasian Soil Science, 32, pp. 533-537.
- de Vries, D. A. (1963), *Thermal properties of soils*, In W. R. van Wijk (ed). Physics of plant environment, North Holland publishing company, Amsterdam, The Netherland, pp. 210-235.
- Hamamoto, S., Moldrup, P., Kawamoto, K. and Komatsu, T. (2010), *Excluded-volume expansion of Archie's law for gas and solute diffusivities and electrical and thermal conductivities in variably-saturated porous media*, Water Resources Research, 46, W06514, doi: 10.1029/2009WR008424.
- Pilegaard, K., Mikkelsen, T. N., Beier, C., Jensen, N. O., Ambus, P. and Ro-Poulsen, H. (2003), *Field measurements of atmosphere-biosphere interactions in a Danish beech forest*, Boreal Environment Research, 8, pp. 315–333.'